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Mulvad, Hans Christian Hansen; Palushani, Evarist; Hu, Hao; Ji, Hua; Galili, Michael; Clausen, Anders; Jeppesen, Palle; Oxenløwe, Leif Katsuo

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Recent Advances in Ultra-High-Speed Optical Signal Processing

H.C. Hansen Mulvad, E. Palushani, H. Hu, H. Ji, M. Galili, A.T. Clausen, P. Jeppesen and L.K. Oxenløwe

DTU Fotonik, Department of Photonics Engineering, Technical University of Denmark, Building 343, DK-2800 Kgs. Lyngby, Denmark, hchm@fotonik.dtu.dk

Abstract *We review recent advances in the optical signal processing of ultra-high-speed serial data signals up to 1.28 Tbit/s, with focus on applications of time-domain optical Fourier transformation. Experimental methods for the generation of symbol rates up to 1.28 Tbaud are also described.*

Introduction

Optical signal processing (OSP) has been the subject of many efforts in the optical communications research community[1]. Indeed, OSP can achieve operation bandwidths which exceed the capability of electrical signal processing (ESP) by several orders of magnitude. Presently, ESP is limited to speeds up to ~100 GHz, as shown for electrical time-division multiplexed (ETDM) signal generation and detection[2]. On the other hand, OSP can explore nonlinear optical phenomena such as the Kerr effect which has a femtosecond response time, thus allowing for speeds exceeding 10 THz. Still, OSP devices based on non-linear optics generally require high optical power and are suitable only for relatively simple functionalities. At low data rates, electronic solutions remain superior to optics both in terms of versatility, performance and energy consumption[3]. Hence, the main potential of OSP in optical communications might lie in scenarios where data signals with very high capacity can be processed optically in a single device, leading to lower energy consumption per bit.

In commercial systems, high-capacity optical data are generated by the dense wavelength division multiplexing (DWDM) of low-speed, electrically generated data channels. Unfortunately, the DWDM format is generally unsuitable for non-linear OSP due to detrimental cross-talk between the parallel channels. On the other hand, such cross-talk can be avoided for serial data where the data-carrying pulses do not overlap. Whereas serial data generated by ETDM are limited to symbol rates of ~100 Gbaud[2], optical time-division multiplexing (OTDM) of short optical pulses has been used to extend the symbol rate up to 1.28 Tbaud[4]. In combination with advanced modulation formats, 1.28 Tbaud OTDM has allowed for the generation of single-channel data capacities up to 10 Tbit/s[5]. The combination of high-capacity single-channels and ultra-fast non-linear OSP could potentially lead to more energy-efficient solutions for future optical communication systems.

In this paper, we review recent demonstrations of non-linear OSP of serial data with capacities up to 1.28 Tbit/s. We focus on time-domain optical Fourier transformation (OFT) which has many useful applications in this area. In particular, OFT can be used for conversion between the serial (OTDM) and parallel (DWDM) formats. Firstly, we describe methods for generation of 1.28 Tbaud data.

Ultra-high-speed signal generation

The generation of Tbaud OTDM data requires high-quality pulses of sub-ps duration and negligible timing jitter[6,7]. In the following, we briefly describe the 1.28 Tbaud OTDM transmitter at DTU Fotonik, which is realised using commercially available components. The essential parts are the pulse source delivering a stable and reproducible output, and a compressor generating a pedestal-free sub-ps output pulse. The pulse source is a solid-state erbium glass oscillating (ERGO) laser from Time-bandwidth Products, delivering 10 GHz repetition rate pulses of duration ~1.5 ps full-width at half maximum (FWHM). The ERGO is synchronized (via a CLX-1100 unit) to a 10 GHz

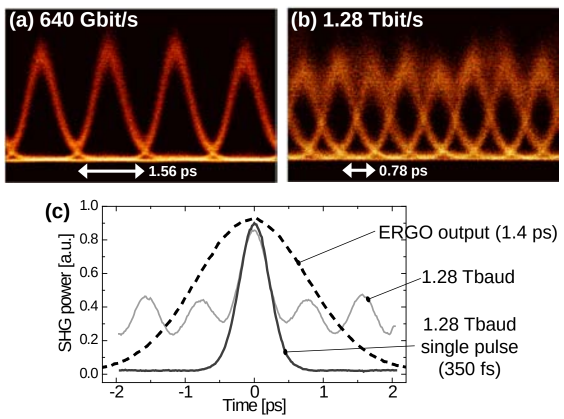

Fig. 1. (a) 640 Gbit/s and (b) 1.28 Tbit/s OTDM-OOK eye diagrams, (c) autocorrelations (with actual pulse FWHMs)[4].

RF clock from a low phase-noise electrical synthesizer (Anritsu MG3691B). The resulting timing jitter of the 10 GHz pulses is <50 fs, which is suitable for 1.28 Tbaud operation[6]. Before multiplexing up to 1.28 Tbaud, the pulse must be compressed down to a FWHM of ~300 fs. Our compression stage is based on self-phase modulation (SPM) in dispersion-flattened highly nonlinear fibre (DF-HNLF) with negative dispersion[8], kindly provided by OFS Fitel Denmark ApS[9]. Combined with filtering, this method allows for the generation of a compressed pulse with negligible pedestal. After compression, the 10 Gbaud pulse is encoded with the desired data format, followed by time-interleaving up to 1.28 Tbaud using a multiplexer (MUX) consisting of 7 successive fibre-based delay-line Mach-Zehnder (MZ) stages (Calmar Optcom bit rate multiplier). The MZ stages are based on polarisation-maintaining (PM) fibres, which are temperature-stabilised against ambient temperature fluctuations. The loss of the MUX (~5 dB per stage) is compensated by intermediate PM-EDFAs. The use of PM components (including the data modulator) reduces the need for polarization control in the transmitter to a single location after the compressor. Altogether, this set-up constitutes a stable and reliable 1.28 Tbaud transmitter with reproducible output pulse characteristics. Typical eye diagrams measured using an optical sampling oscilloscope (OSO) are shown in Fig. 1 (a) and (b). Note that the OSO resolution (~1 ps) is insufficient for resolving the 1.28 Tbaud data. The autocorrelations in Fig. 1 (c) compare the 1.28 Tbaud pulse (FWHM 350 fs) with the uncompressed ERGO output pulse (1.4 ps).

Optical signal processing demonstrations

Various types of optical signal processing have been demonstrated for ultra-high-speed OTDM data[1,10], using not only fibres, but also compact devices such as semiconductor optical amplifiers (SOA), periodically poled lithium niobate waveguides (PPLN), chalcogenide waveguides and silicon nanowires. For the detection of OTDM data, optical demultiplexing and clock recovery are required. Demultiplexing of 1.28 Tbaud OTDM data has been achieved using HNLF[4], chalcogenide[11], and silicon[12]. Pre-scaled clock recovery has been shown for 640 Gbit/s data using a SOA[13], PPLN[14], or HNLF[15] as optical phase-comparator. Examples of OSP that process the entire OTDM data content are wavelength conversion and regeneration. Wavelength conversion can be employed for high-speed data routing and has

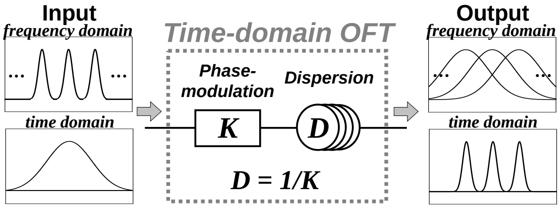

Fig. 2. Time-domain OFT (for frequency-to-time conversion)

been demonstrated at 640 Gbit/s in HNLF[16,17] and silicon[18] (within FEC limits). Optical regeneration could extend the transmission reach of ultra-high-speed serial data, and it is therefore an important but also challenging functionality. So far, reports include amplitude-regeneration of 640 Gbit/s data in PPLN[19] (with wavelength conversion) and of 160 Gbit/s data in HNLF[20].

Time-domain optical Fourier transformation

Time-domain OFT[21] converts the power profile of an optical waveform from the frequency- to the time-domain by a balanced combination of parabolic phase-modulation (chirp rate K) and second order chromatic dispersion D, as shown in Fig. 2. Time-to-frequency conversion is achieved by D followed by K. Several useful applications of OFT for high-speed OTDM data have been demonstrated. For example, linear transmission impairments can be mitigated using OFT to transfer the unaltered data spectrum into the time-domain[21], which has been employed for a 640 Gbaud transmission over 525 km[22]. The OFT principle enables ultra-high-speed electro-optic phase comparison with $LiNbO_3$ modulators, which has been used for pre-scaled 40 GHz electrical clock recovery from 640 Gbaud OTDM data[23]. The SNR in coherent detection of high-speed multi-level OTDM data can be significantly improved using a similar method to narrow the demultiplexed pulse

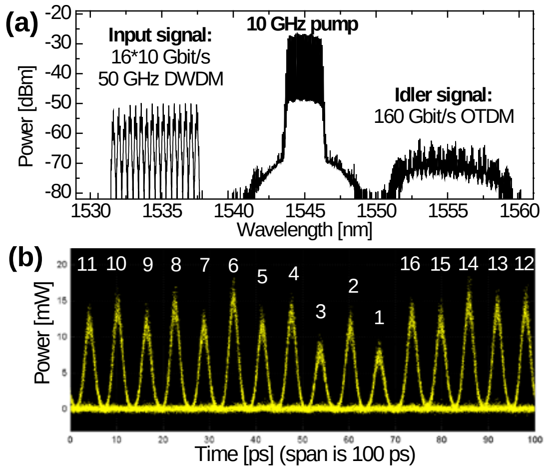

Fig. 3. DWDM-to-OTDM conversion of a 16×10 Gbit/s 50 GHz DWDM signal by OFT. (a) Spectrum after FWM in a 100 m PM-HNLF, (b) OSO eye diagram of the 160 Gbit/s DWDM-to-OTDM converted signal (all 16 channels).[26]

spectrum before demodulation[24]. Flat-top pulses for timing-jitter-tolerant demultiplexing can be generated by OFT frequency-to-time conversion of a flat-top spectral profile[25].

Recently, we have demonstrated that OFT allows the conversion of large numbers of data channels between the OTDM and DWDM formats in a single optical device[26,27]. In these experiments, a four-wave mixing (FWM) process using chirped pump pulses is employed instead of electro-optic phase-modulation to achieve larger OFT bandwidth[28]. DWDM-to-OTDM conversion is achieved by frequency-to-time OFT (as in Fig. 2). Fig. 3 shows results from the conversion of 16×10 Gbit/s OOK DWDM data on a 50 GHz grid to 160 Gbit/s OTDM[26]. All 16 channels were subsequently time-demultiplexed with error-free performance. An average DWDM-to-OTDM conversion penalty of 2.1 dB was measured. OTDM-to-DWDM conversion is achieved by time-to-frequency OFT. Fig. 4 shows results from the conversion of 640 Gbit/s OTDM-OOK data to 25 GHz DWDM[27]. Error-free operation was achieved for more than half of the 64×10 Gbit/s tributaries. This OTDM-to-DWDM technique could enable a much simpler and less energy-consuming receiver for high-speed OTDM by replacing single-tributary demultiplexers (see e.g. refs[4,11,12]). As another potential application, DWDM regeneration might be achievable by combining OFT-based DWDM-to-OTDM and OTDM-to-DWDM conversions with intermediate OTDM regeneration.

Conclusion

Continuous progress is being made in the optical signal processing of ultra-high speed serial data, both in terms of improved non-linear devices and novel applications. Further research might pave the way for energy-efficient solutions for future high-capacity communication systems.

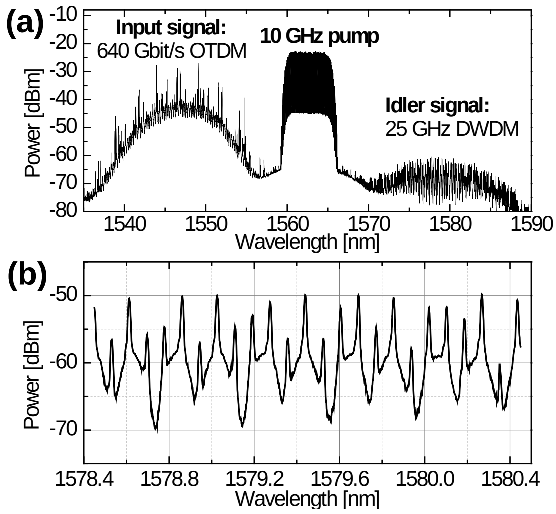

Fig. 4. OTDM-to-DWDM conversion of 640 Gbit/s OOK data to 25 GHz DWDM by OFT: (a) Spectrum after FWM in a 50 m HNLF, (b) zoom-in on the idler DWDM spectrum, showing nine 10 Gbit/s channels (resolution 0.01 nm).[27]

References

[1] A. E. Willner et al., IEEE J. Sel. Top. Quantum Electron. **17**, 320 (2011).
[2] C. Schubert et al., Proc. ECOC'06, Tu1.5.5 (2006).
[3] R. S. Tucker et al., IEEE Photon. J. **3**, 821 (2011).
[4] H. C. H. Mulvad et al., Electron. Lett. **45**, 280 (2009)
[5] T. Richter et al., Proc. OFC'11, PDPA9 (2011).
[6] M. Jinno, IEEE J. Quantum Electron. **30**, 2842 (1994).
[7] A. T. Clausen et al., Proc. LEOS'03, TuY2 (2003).
[8] F. Futami et al., Electron. Lett. **34**, 2129 (1998).
[9] C. G. Joergensen et al., Proc. ECOC'03, We3.7.6 (2003)
[10] L. K. Oxenløwe, Proc. IEEE Photonics Conference 2011, WEE1 (tutorial) (2011).
[11] T. D. Vo et al., Opt. Express. **18**, 17252 (2010).
[12] H. Ji et al., Proc. OFC'10, PDPC7 (2010).
[13] E. Tangdiongga et al., Proc. ECOC'07, PD 1.2 (2007).
[14] L. K. Oxenløwe et al., Electron. Lett. **44**, 370 (2008).
[15] B. P.-P. Kuo et al., IEEE Photon. Technol. Lett. **23**, 191 (2011).
[16] H. Sotobayashi et al., Proc. OFC'02, WM2 (2002).
[17] M. Galili et al., IEEE J. Sel. Top. Quantum Electron. **14**, 573 (2008).
[18] H. Hu et al., Opt. Express **19**, 19886 (2011).
[19] A. Bogoni et al., J. Lightwave Technol. **30**, 1829 (2012).
[20] S. Watanabe et al., Proc. OFC'03, PD16 (2003).
[21] M. Nakazawa et al. IEEE Photon. Technol. Lett. **16**, 1059 (2004).
[22] T. Hirano et al., IEEE Photon. Technol. Lett. **22**, 1042 (2010).
[23] H. C. H. Mulvad et al., Proc. ECOC'10, Mo.1.A.6 (2010).
[24] K. Kasai et al., IEEE Photon. Technol. Lett. **24**, 416 (2012).
[25] E. Palushani et al., IEEE J. Quantum Electron. **45**, 1317 (2009).
[26] H. C. H. Mulvad et al., Proc. ECOC'11, Mo.1.A.5 (2011).
[27] H. C. H. Mulvad et al., Opt. Express **19**, B825 (2011).
[28] M. Foster et al., Nature **456**, 81 (2008).